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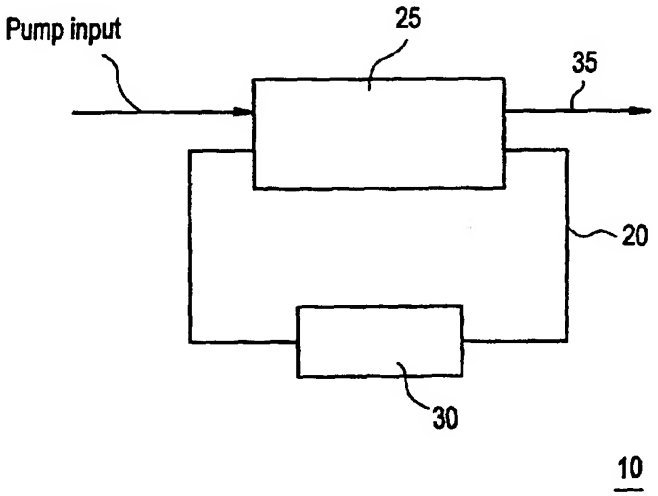
(54) Title: MULTI-WAVELENGTH LASER USABLE FOR WDM APPLICATIONS AND INTERFEROMETRIC SENSORS



(57) Abstract: A multi-wavelength laser (10) includes an optical loop (20) having a single optical cavity that supports a plurality of longitudinal modes, wherein the optical loop has a common gain medium (25) to supply the necessary optical gain to provide for a plurality of lasing longitudinal modes at a plurality of lasing wavelengths. A wavelength selector (30) is insertable into the optical loop within the optical path for selecting at least one lasing longitudinal mode (35) from the plurality of longitudinal modes. Although not exclusively, the multi-wavelength laser (10) is usable for WDM interferometric sensing (240).

WO 01/03254 A2

MULTI-WAVELENGTH LASER USABLE FOR WDM APPLICATIONS AND INTERFEROMETRIC SENSORS

BACKGROUND OF THE INVENTION

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is based upon U.S. Provisional Application Serial Number 60/142,208, filed on July 2, 1999, from which the benefit of priority pursuant to 35 USC § 120 is hereby claimed, and the full content which is incorporated herein by references as though fully set forth.

Field of the Invention

The present invention relates generally to lasers, particularly to multi-wavelength lasers and to Interferometric Sensors that are Wavelength Division Multiplexed and utilize multi-wavelength laser sources.

Technical Background

To handle the explosion for data capacity in telecommunication systems, system designs are using wavelength division multiplexing (WDM) to obtain more data capacity. Thus, more laser sources of higher quality are needed to build and

characterize WDM systems. A significant and growing fraction of the total cost in WDM systems is due to laser sources. Currently each WDM channel requires its own laser source. For example, a telecommunication system which is being designed for eighty wavelengths operation will need eighty source lasers. Future systems will be requiring even more laser wavelengths as the systems expand. Large cost savings can be realized by developing cheaper laser sources. The telecommunication systems as well as the test and measurement systems for WDM systems will realize the cost savings due to cheaper laser sources.

One way to make laser sources cheaper is to exploit the natural characteristics of Erbium Doped Fibers (EDF). The wide bandwidth of the EDF gain profile provides an ideal gain medium to design a multi-wavelength laser. The longitudinal modes of the laser cavity, which lase simultaneously at multiple wavelengths, are formed by using standard telecommunication components such as gratings, fiber Bragg gratings, thin films, phasors, and liquid crystal devices. Erbium Doped Fiber Laser (EDFL) wavelengths can be easily added or dropped. It is desired that an improved EDFL will be able to provide the necessary laser wavelengths to cover the ITU grid or any desired subset.

The need for cheaper lasers transcends the telecommunication industry. As more efficienct designs of complex systems involving engineering structures, adaptive structures and manufacturing processes evolve, the ultimate limits of the engineering materials used in the systems are being approached. The reduced margins of safety for the materials used in the design of the complex systems will require the use of sensing systems to measure displacements, strain and temperature at a number of critical locations. These measurements will allow the designs to maintain safety and reliability.

Traditional electronic based sensors such as strain gauges, thermocouples, and resistive displacement sensors work well for applications which require only a relatively small number of sensors. To build large sensing arrays from electrical based sensors, the designer would be required to use complex routing, elaborate harnessing and delicate switching schemes. The additional wiring and electronics would interfere with the functionality of the structure even if state of the art thin film or MEMS sensors are used.

Optical sensors can reduce the complexity and the amount of routing because the interferometric sensors are non-contacting and can be WDM. Therefore, the optical sensor does not need to be mounted to the test specimen. Since the interferometric sensors can be WDMed or otherwise multiplexed, a single transmission fiber can send/receive light to/from multiple transducers. The multi-wavelength laser provides for the efficient generation and transmission of the optical energy to interrogate the optical sensors.

SUMMARY OF THE INVENTION

One aspect of the present invention is the generation of a laser synthesizer. A multi-wavelength laser includes an optical loop having a plurality longitudinal modes and a wavelength selector insertable into the optical loop for selecting at least one particular longitudinal mode from the plurality of modes for synthesizing desired laser wavelengths.

In another aspect, the present invention includes a wavelength division multiplexor as the wavelength selector.

Yet another aspect of the present invention is the construction of WDM interferometric sensors which efficiently utilize the multi-wavelength laser source.

Additional features and advantages of the invention will be set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from that description or recognized by practicing the invention as described herein, including the detailed description which follows, the claims, as well as the appended drawings.

It is to be understood that both the foregoing general description and the following detailed description are merely exemplary of the invention, and are intended to provide an overview or framework for understanding the nature and character of the invention as it is claimed. The accompanying drawings are included to provide a further understanding of the invention, and are incorporated in and constitute a part of this specification. The drawings illustrate various embodiments of the invention, and together with the description serve to explain the principles and operation of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a multi-wavelength laser in accordance to the teachings of the present invention;

FIG. 2 is a block diagram of the multi-wavelength laser 10 of FIG. 1, wherein the optical loop 20 is a Fabry-Perot (FP) laser cavity and the wavelength selector 30 is a wavelength division multiplexor (WDM) in accordance to the teachings of the present invention;

FIG. 3 is a block diagram of the multi-wavelength laser 10 of FIG. 1, wherein the optical loop 20 is a ring laser cavity and the wavelength selector 30 is a liquid crystal cross-connect (LCX) in accordance to the teachings of the present invention;

FIG. 4 is a block diagram of the multi-wavelength laser 10 of FIG. 1, wherein the optical loop 20 is a Fabry-Perot laser cavity and the wavelength selector 30 is a liquid crystal cross-connect (LCX) in accordance to the teachings of the present invention;

FIG. 5 is a block diagram of the multi-wavelength laser 10 of FIG. 2 used in an optical injection locked sensing system in accordance to the teachings of the present invention;

FIG. 6 is a Bragg fiber tip portion of an interferometric sensing system in accordance to the teachings of the present invention; and

FIG. 7 is a sensing system which consists of heterodyne interferometers that are wavelength division multiplexed, using multiple Bragg fiber tip portions of FIG. 6, in accordance to the teachings of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Reference will now be made in detail to the present preferred embodiments of the invention, examples of which are illustrated in the accompanying drawings. Wherever possible, the same reference numbers will be used throughout the drawings to refer to the same or like parts. An exemplary embodiment of the multi-wavelength laser of the present invention is shown in FIG. 1, and is designated generally throughout by reference numeral 10.

Referring to FIG. 1, a multi-wavelength laser 10 includes an optical gain medium 25, an optical loop 20 having a plurality of longitudinal modes, and a

wavelength selector 30 that is insertable into the optical loop 20 for selecting at least one longitudinal mode 35 from the plurality modes for synthesizing desired laser wavelengths.

Referring to FIG. 1, the present embodiments of the multi-channel EDFLs use two different classes of optical loops 20 of FIG. 1: First, the Fabry-Perot of FIGS. 2 and 4; Second, the Ring Laser of FIG. 3, but other laser cavity classes are usable in accordance with the teachings of the present invention. Within each cavity class, multiple optical paths are formed in the WDM 223 of FIG. 2 or in the Liquid Crystal Cross-connect (LCX) 350 of FIG. 3, as provided by the LCX taught in U.S. patent number 5,414,540. The functionality of the LCX 350, or other switches or wavelength selectors 30 of FIG. 1, provides for a convenient way to dynamically change the gain spectrum of the optical loop 20. Thus the lasing amplitude and wavelengths 35 of FIG. 1 can be externally controlled by the LCX 350 of FIG. 3 or by the combination of wavelength control by a wavelength division multiplexor 223 and amplitude control by the variable optical attenuator (VOA) 260 in FIG. 2. Hence, the LCX 350 of FIGS. 3-4 provides for dynamic wavelength selection, multiple lasing wavelengths, and optical power equalization/distribution amongst the lasing wavelengths in the EDFL. The intracavity wavelengths can be monitored by an Optical Spectrum Analyzer or by a Wavelength meter 37 from a monitoring port 36 in the LCX 350.

Because the present invention provides multiple wavelengths, there must be multiple longitudinal modes which can be considered to be uncoupled optical cavities. However component-wise, the cavities share one gain medium, share at least one mirror in a FP configuration of FIG. 2 or FIG. 4, (Ring lasers such as FIG. 3 do not have mirrors), and a majority of the optical path. Depending on the configuration it is the wavelength selector, such as a WDM device which provides for the controlled definition of the longitudinal modes. Hence, a multi-wavelength laser which can simultaneously emit multiple wavelengths is provided whose multiple wavelengths are dynamically controlled, selected or tuned by the wavelength selector. Advantageously, a reduced component count results with such a physical cavity, as taught by the present invention.

Pumping a single gain medium 25 of FIG. 1 in the preferred form of an erbium doped fiber (EDF) 250 of FIG. 2 with a 980 nm laser source 202 provides the active

gain medium. The first WDM 221 combines the optical pump energy with optical signal energy in the 1550 nm telecommunication band. The 980 nm pump light activates the EDF to provide gain for the optical energy in the 1550 nm band. The second WDM 222 separates the excess 980 nm pump energy from the signal energy at 1550 nm. The WDMs 221 and 222 ensure that the pump laser light does not form an optical loop.

In the ring laser cavity of FIG. 3, the gain spectrum of the EDF 250 and the continuity of the optical electromagnetic fields within the ring cavity 20 determine the potential lasing wavelengths 35. The continuity requirement determines a set of discrete wavelengths that may resonate in the cavity 20 and the EDF gain spectrum determines which resonant wavelengths will have the potential to lase.

The Fabry-Perot cavity 20 of FIGS. 2, 4, and 5 operates in a similar manner except that the continuity requirement is supplemented by boundary conditions at the two ends such as mirrors 401 and 402 of FIG. 4. Thus the Faby-Perot cavity 20 of FIG. 4 specifies the resonant wavelengths and the gain medium determines the wavelengths 35 that lase.

Instead of using the second mirror 402 of FIG. 4, the third wavelength division multiplexor (WDM) 223, at least one Variable Optical Attenuator (VOA) 260 and at least one Bragg grating 242 can be substituted in its place in FIG. 2 which will also remove the need for the LCX 350.

FIG. 2 shows the schematic of such a multi-channel EDFL. Multiple optical paths are formed between the 100% mirror 401 and the reflective Bragg gratings 242. As before, an active gain medium is provided by pumping the EDF 250 with a 980 nm laser source 202. The third WDM 223 apportions the gain spectrum of the EDF 250 into separate optical paths. As stated previously, the Variable Optical Attenuator (VOA) 260 provides amplitude control for the individual laser wavelengths 262. The reflective Bragg gratings 242 determine the laser linewidth and center wavelength. The center wavelength can be tuned by changing the ambient temperature of the Bragg gratings 242, which changes the optical path length of each sub-cavity.

To actively stabilize/tune the laser wavelengths, a heterodyne interferometer is optionally used to monitor the leakage light transmitted through the Bragg grating 242. A stable reference laser 204 at a specified wavelength λ_0 is used to precisely determine

the center wavelength of the first laser cavity at λ_1. Light from the reference laser 204 and the first EDFL cavity is mixed in a 1X2 mixing coupler 230. The mixed light from the coupler 230 is incident onto a photodiode 240. The photodiode 240 monitors the intensity fluctuations of the mixed light. The mixed light intensity is amplitude modulated at the frequency difference between λ_0 and λ_1. The control electronics 270 keep a specified frequency difference (wavelength) constant by adjusting the temperature of the fiber Bragg grating 242 through the use of a Thermoelectric Controller (TEC) 280. Once λ_1 is established, λ_1 is used to set λ_2 and λ_2 is used to set λ_3. This process is cascaded to accurately establish the center wavelengths λ_1 through λ_N with respect to the reference wavelength to create a laser synthesizer or wavelength standard or generator. The last N-coupler 640 would not be necessary at the end of the cascaded chain where no more wavelengths are needed. However, the open port at the last N-coupler 640 allows the flexibility of adding more wavelengths if desired.

By applying WDM interferometric sensors and the multi-wavelength laser source to mechanical sensing problems, in accordance with the teachings of the present invention, a broad range of inventive robust sensing systems can be developed. Novel multi-channel interferometers can be developed using telecommunication components such as fiber Bragg gratings and thin film devices. These interferometers can be used for non-contacting displacement, strain and temperature measurements, such as for non-evasively monitoring the acoustic resonances at critical points of mechanical structures.

The basic building blocks of the WDM displacement sensor that can be incorporated into an array is shown in FIG. 6. The optical sensor will be a heterodyne interferometer that uses a Bragg Fiber Tip (BFT) 642. Two closely spaced wavelengths are injected into a first 1X2 coupler 630 with a fiber Bragg grating 642 at the end of the sensing leg of a second coupler 640. One of the wavelengths (λ_1) is reflected by the grating 642 and the other wavelength (λ_2) exits the grating end of the fiber 660 onto the surface of the test specimen, represented by a moving reflector 650. Some of the light, which exits the fiber 660, is scattered back into the fiber 660. Both wavelengths of light travel back through the second 1X2 coupler 640 and are evenly split into the two legs of the coupler 640. The backreflected light that is guided to the isolator 670 is

absorbed. The backreflected light (λ_1, λ_2) that propagates to the photodiode 240 is incident and mixed onto the photodiode 240.

The photodiode 240 monitors the intensity fluctuations of the mixed light. The mixed light intensity is amplitude modulated at a carrier frequency, which is the frequency difference between λ_1 and λ_2. The movement of the test specimen frequency modulates the carrier frequency via the Doppler shift of λ_2. The test specimen also phase modulates the carrier via changes in displacements which is equivalent to the Doppler shift. The modulated carrier signal is either frequency demodulated (velocity) or phase demodulated (displacement) by the systems electronics 270 to monitor the motion of the test specimen 650. The data acquisition system 680 records the displacement measurements in real-time and archives the data which is to be used to analyze the motion of the moving reflector.

Since both wavelengths travel within the same fiber 660 over the majority of the optical paths, the interferometric configuration is robust with respect to optical path length changes due to temperature, vibration and acoustics. These noise sources should have minimal effect on the measurements made by the interferometer of FIG. 6. Thus this sensing configuration will be easier to implement in the manufacturing environment than conventional interferometers.

Several heterodyne interferometers using Bragg fiber tips can be efficiently combined to create an array of sensors, such as in FIG. 7. Multiple pairs of closely spaced wavelengths (i.e. λ_1, λ'_1) are routed to individual interferometers by the wavelength division multiplexor (WDM) 223. The resulting sensor array is capable of providing displacements at discrete locations. This displacement information can then be used in modal analysis to determine the quality or health of a mechanical structure. The design shown in FIG. 7 allows the multi-wavelength laser source to be in a central location and to service other applications.

The EDFL technology can be modified to incorporate the interferometer as part of the laser cavity. The schematic of an injection locked fiber laser with multiple channels for a heterodyne sensing system is shown in FIG. 5. This configuration reduces the alignment sensitivity of the component interferometers. The gain and single mode properties of the optical path 262 amplify and mode filters the

backscattered light from the moving reflector. Thus dynamic and inefficient coupling of backscattered light into the optical path within the laser can be tolerated.

Referring to FIG. 5, the multiple laser cavities 262 are formed between the 100% mirror 401 and the reflective Bragg gratings 242. Pumping the EDF 250 with a 980 nm laser source 202 provides an active gain medium as before in FIG. 2. The WDM 223 apportions the gain spectrum of the EDF 250 into separate optical paths 262. The Variable Optical Attenuator (VOA) 260 provides amplitude control for the individual laser wavelengths. The reflective Bragg gratings 242 determine the laser linewidth and center wavelength of each of the individual laser wavelengths. The center wavelengths can be tuned by changing the ambient temperature of the Bragg gratings 242, which changes the optical path length.

A heterodyne interferometer is formed between two adjacent cavities. Referring back to FIG. 5, the laser light is tapped out of the odd numbered sub-cavities after the light has been transmitted through the Bragg gratings 242. The interrogating laser at a nominal wavelength, λ_1, is used to measure the surface motion of the object under test, as represented by the moving reflector 650. Light from the reference laser, λ_2, and the interrogating laser is mixed in a 1X2 coupler 230. The mixed light from the coupler 230 is incident onto a photodiode 240. The photodiode 240 produces a carrier signal at the frequency difference between λ_1 and λ_2. The control electronics 270 keeps the nominal carrier frequency constant by adjusting the temperature of the fiber Bragg grating 242 through the use of a Thermoelectric Controller (TEC) 280.

Some of the light λ_1 that is exiting the interrogating fiber is scattered back into the fiber. This recaptured light reenters the laser cavity and perturbs the operating point of the cavity. The cavity perturbation can be monitored by an amplitude (self-mixing) or a frequency (phase locking) effect. The heterodyne interferometer monitors the frequency perturbations which are a function of the object's motion. Thus a sensitive and robust displacement sensor is constructed.

Reference is made to U.S. Patent No. 4,928,527 for a more detailed explanation of optical interfermetric sensing measurements where a grating fiber end was not taught, as in the present invention.

It will be apparent to those skilled in the art that various modifications and variations can be made to the present invention without departing from the spirit and scope of the invention. Thus, it is intended that the present invention cover the modifications and variations of this invention provided they come within the scope of the appended claims and their equivalents.

What is claimed is:

1. A method for laser synthesizing a plurality of different wavelengths, the method comprising the steps of:

providing a laser having a plurality of optical wavelengths;

selecting at least one optical wavelength from the plurality of optical wavelengths; and

referencing said at least one optical wavelength to an internal or external reference source.

2. The method of claim 1 wherein the step of referencing includes optical interferometric sensing for the measurement of dynamic displacements.

3. A multi-wavelength laser comprising:

an optical loop having a single optical cavity that supports a plurality of longitudinal modes, wherein the optical loop has a common gain medium to supply the necessary optical gain to provide for a plurality of lasing longitudinal modes at a plurality of lasing wavelengths; and

a wavelength selector that is insertable into the optical loop within the optical path for selecting at least one lasing longitudinal mode from the plurality of longitudinal modes.

4. The multi-wavelength laser of claim 3 wherein the optical loop comprises a Fabry-Perot laser cavity having an erbium doped fiber for supporting broadband wavelength amplification of the plurality of lasing wavelengths.

5. The multi-wavelength laser of claim 3 wherein the optical loop comprises a ring laser cavity having an erbium doped fiber.

6. The multi-wavelength laser of claim 3, wherein the wavelength selector comprises a WDM to select at least one desired lasing wavelength from the plurality of lasing longitudinal modes.

7. The multi-wavelength laser of claim 6, wherein the wavelength selector further comprises a VOA to control the amplitude of at least one desired lasing wavelength from the plurality of lasing longitudinal modes.

8. The multi-wavelength laser of claim 3, wherein the wavelength selector ~~further~~ comprises an LCX to control the desired lasing wavelengths and amplitudes from the plurality of longitudinal modes.

FIG. 1

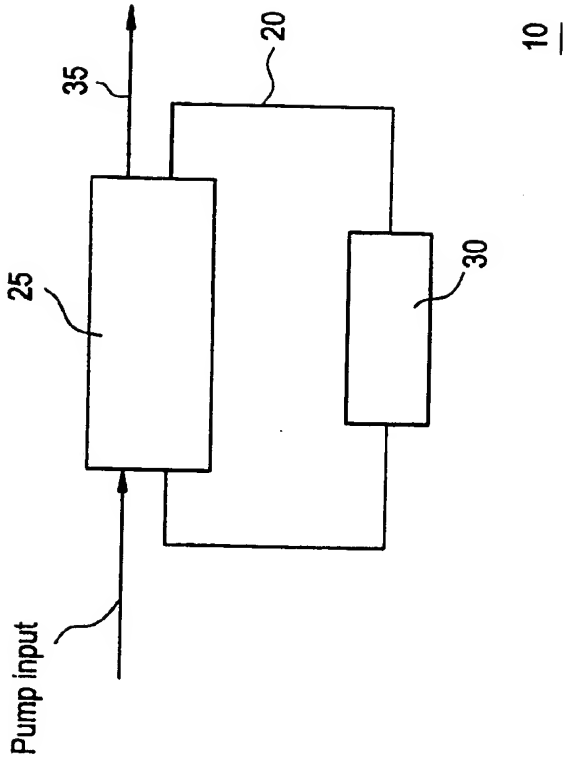


FIG. 2

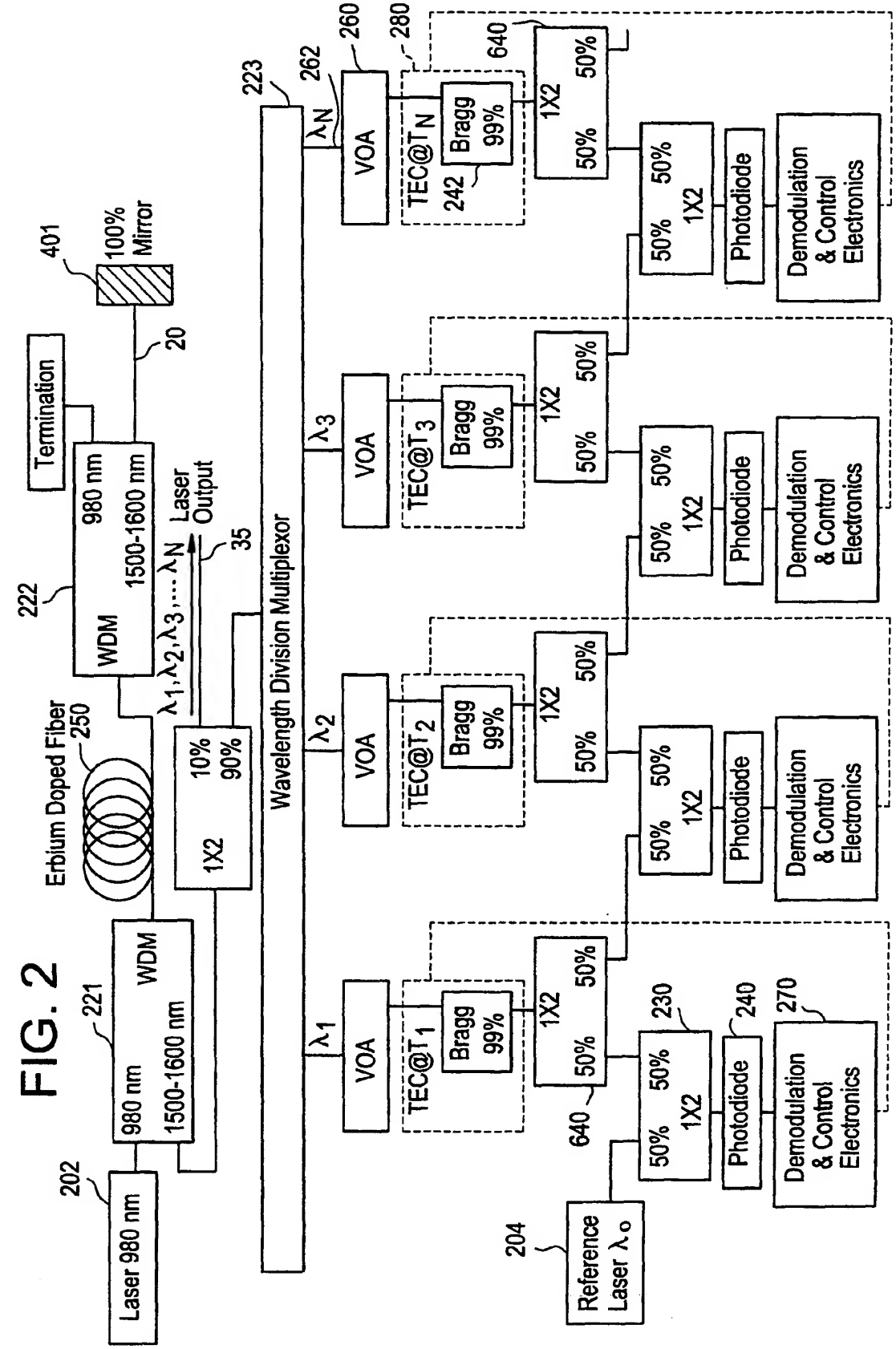

Laser 980 nm
202
980 nm
1500-1600 nm
WDM
221
Erbium Doped Fiber
250
1X2
10%
90%
$\lambda_1, \lambda_2, \lambda_3, \ldots \lambda_N$
Laser Output
35
WDM
980 nm
1500-1600 nm
222
Termination
100% Mirror
401
20
Wavelength Division Multiplexor
223
λ_1
λ_2
λ_3
λ_N
VOA
260
262
TEC@T_1
TEC@T_2
TEC@T_3
TEC@T_N
Bragg 99%
242
280
1X2
50%
50%
640
Reference Laser λ_o
204
50% 50% 1X2
230
Photodiode
240
Demodulation & Control Electronics
270

FIG. 3

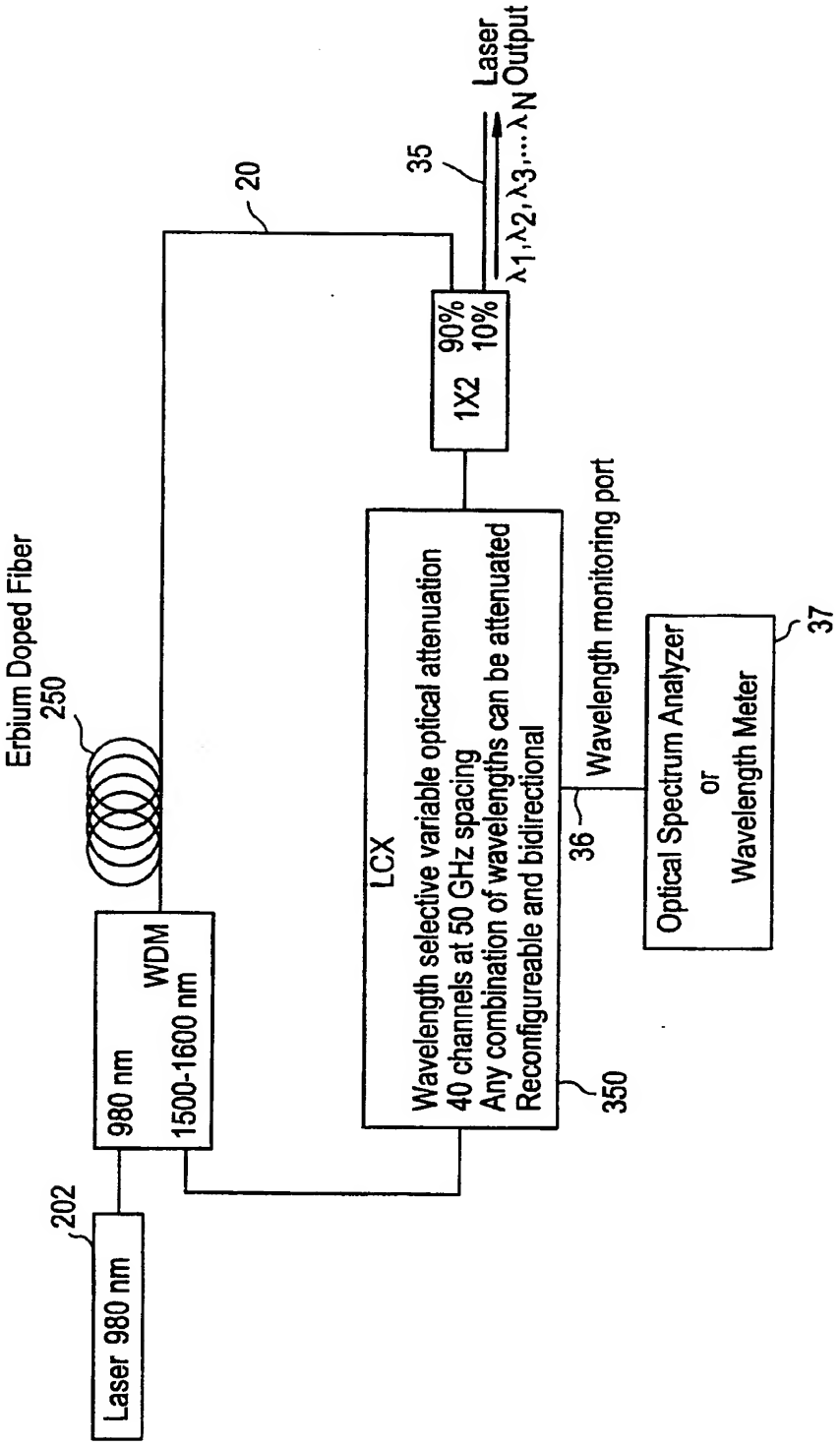

Laser 980 nm
202
980 nm
WDM
1500-1600 nm
Erbium Doped Fiber
250
20
35
Laser Output
$\lambda_1, \lambda_2, \lambda_3, \ldots \lambda_N$
1X2
90%
10%
LCX
Wavelength selective variable optical attenuation
40 channels at 50 GHz spacing
Any combination of wavelengths can be attenuated
Reconfigureable and bidirectional
350
Wavelength monitoring port
36
Optical Spectrum Analyzer
or
Wavelength Meter
37

FIG. 4

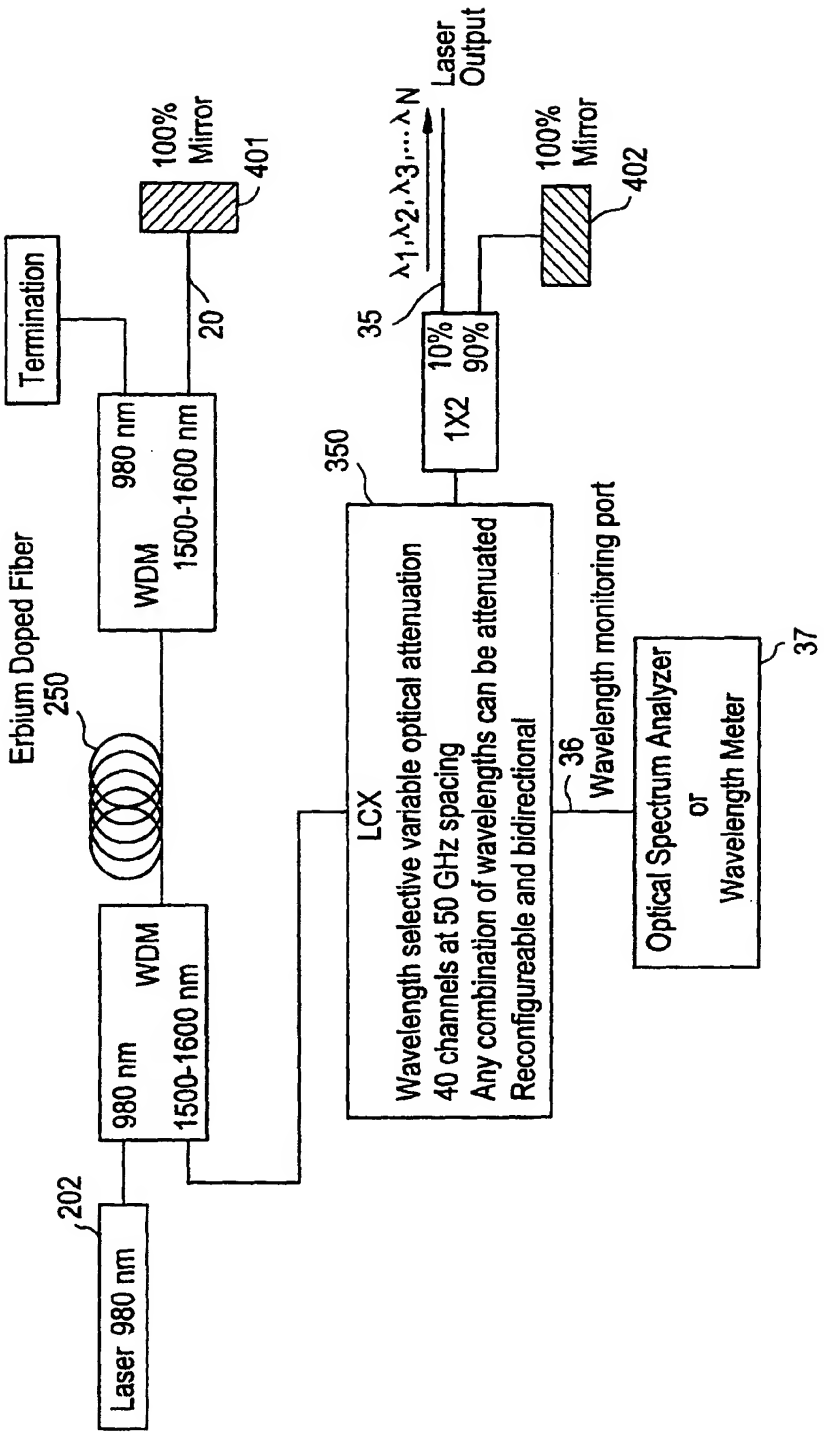

Laser 980 nm
202
980 nm
WDM
1500-1600 nm
Erbium Doped Fiber
250
980 nm
WDM
1500-1600 nm
Termination
100%
Mirror
401
20
350
LCX
Wavelength selective variable optical attenuation
40 channels at 50 GHz spacing
Any combination of wavelengths can be attenuated
Reconfigureable and bidirectional
36
Wavelength monitoring port
Optical Spectrum Analyzer
or
Wavelength Meter
37
35
λ1,λ2,λ3,...λN
Laser
Output
1X2
10%
90%
100%
Mirror
402

FIG. 5

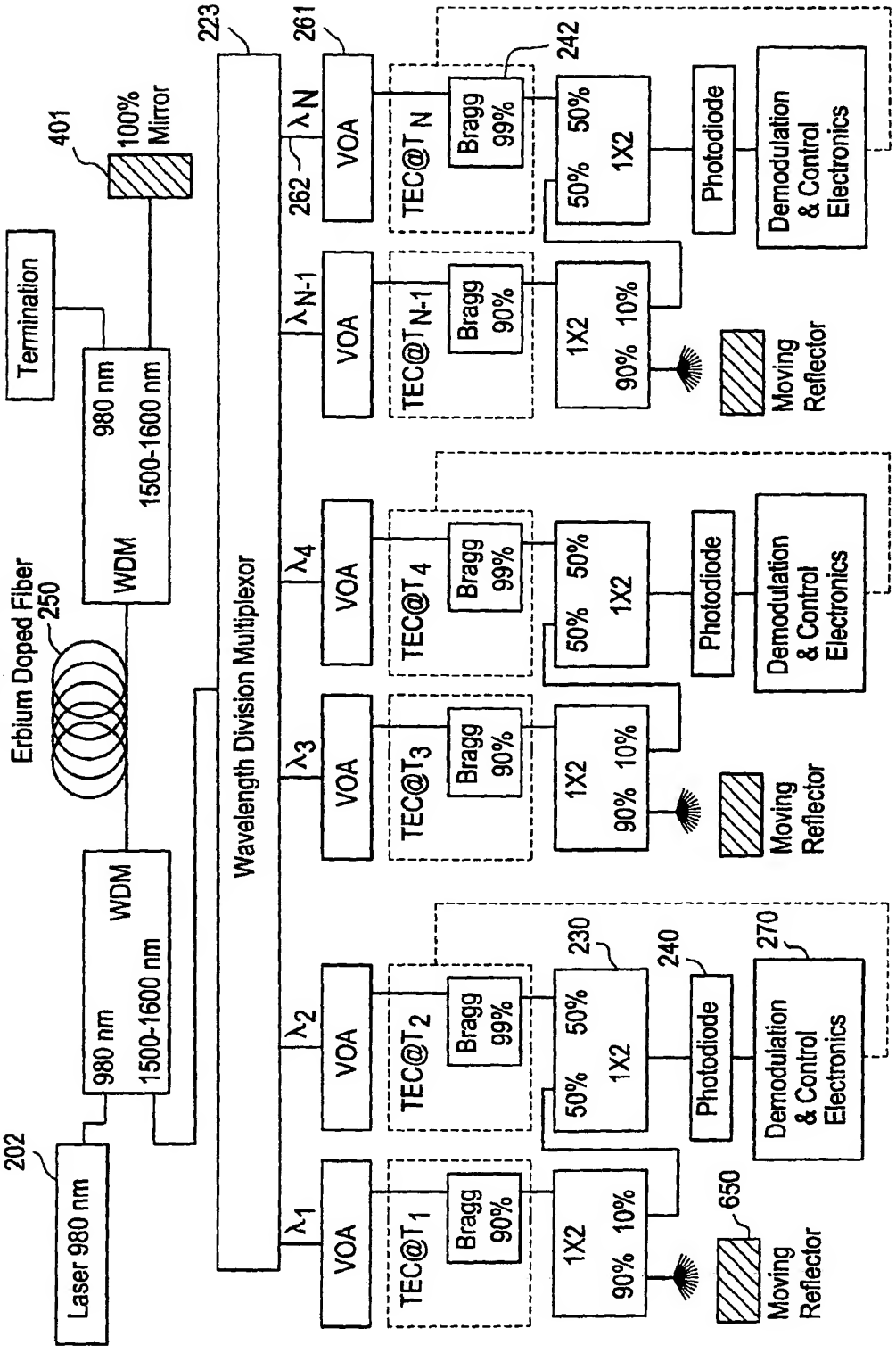

Laser 980 nm
202
980 nm
WDM
1500-1600 nm
Erbium Doped Fiber
250
980 nm
WDM
1500-1600 nm
Termination
401
100% Mirror
Wavelength Division Multiplexor
223
λ1
λ2
λ3
λ4
λN-1
λN
262
261
VOA
TEC@T1
TEC@T2
TEC@T3
TEC@T4
TEC@TN-1
TEC@TN
Bragg 90%
Bragg 99%
1X2 90% 10%
50% 50% 1X2
230
240
242
Photodiode
Demodulation & Control Electronics
270
Moving Reflector
650

FIG. 6

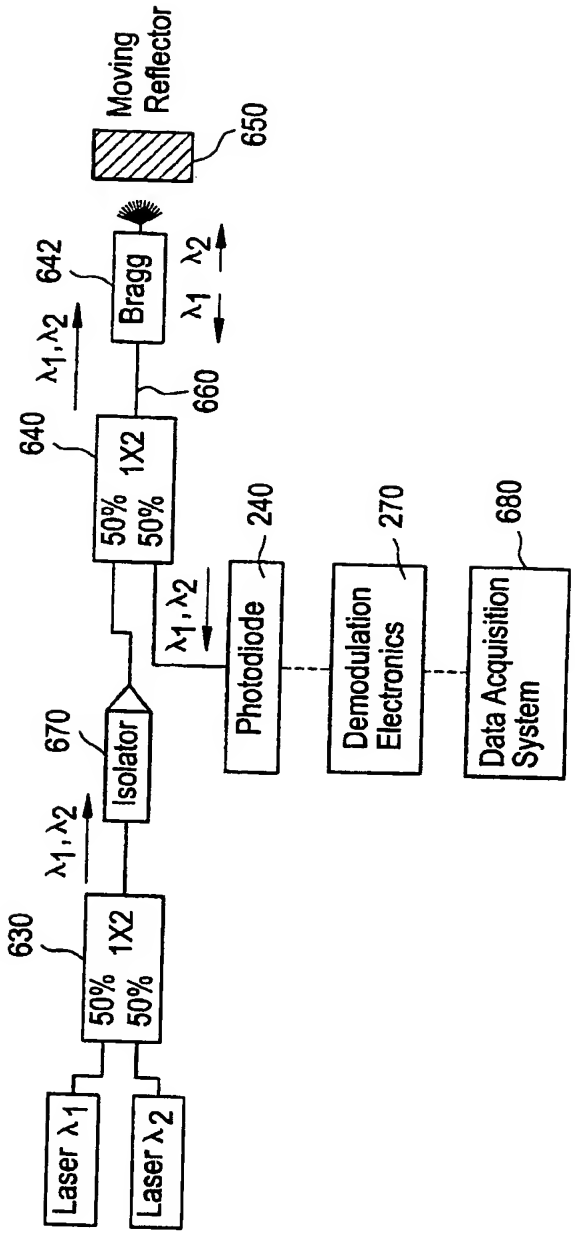
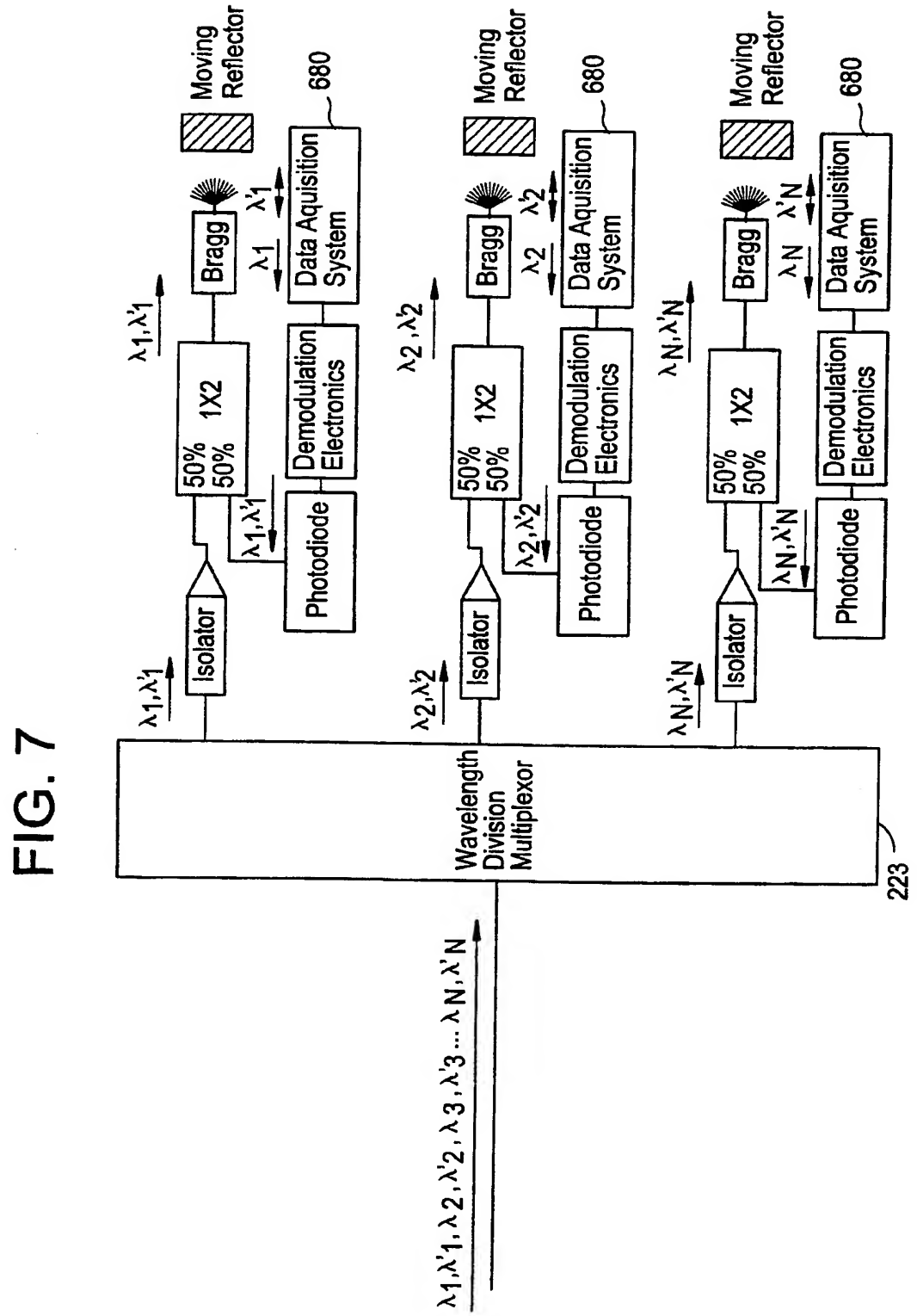

Moving Reflector
650
Bragg
642
λ1, λ2
λ2
λ1
660
640
50% 50% 1X2
λ1, λ2
240
Photodiode
270
Demodulation Electronics
680
Data Acquisition System
670
Isolator
λ1, λ2
630
50% 50% 1X2
Laser λ1
Laser λ2

FIG. 7


Moving Reflector
Bragg
Data Aquisition System
680
Demodulation Electronics
Photodiode
50% 50% 1X2
Isolator
Wavelength Division Multiplexor
223
λ1,λ'1,λ2,λ'2,λ3,λ'3 ... λN,λ'N